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STUDY OF B PARTICLE AND CHARMED PARTICLE PRODUCTION AND DECAY USING A HIGH RESOLUTION STREAMER CHAMBER

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Proposal for a Study of B Particle and Charmed Particle Production and Decay

I. Introduction

We propose to use an improved version of the Yale FNAL high resolution streamer chamber (HIRSC) and muon detector with the addition of a downstream toroidal magnet for muon momentum measurements, to study the hadronic production and subsequent decay of particles carrying the B quantum number and to greatly improve and extend our earlier work on the production and decay of charmed particles. A preprint of the results of that experiment (E-490) which has been submitted to the Physical Review Letters is attached. We propose to use the neutron beam, suitably collimated, in a 600 hour run in P-East. We thus propose to move our E-490 apparatus (including the muon detector) to P-East some time after our streamer chamber test run in M1 in the spring of 1980. Due to the topical character of this proposal we are very eager to run the experiment as soon as possible. In particular the fall running period of 1980 appears to be an ideal time. As will be discussed in greater detail below, the use of neutrons (which do not leave tracks in the chamber) as the incident beam permits an increase, relative to a charged incident beam, of a factor of ~40 in flux per pulse, and a corresponding increase of a factor of ~10 in the (dead time limited) rate of events. We note that this limit, corresponding to 3.9×10^7 neutrons per pulse, is set by the trigger rate ($\langle N_T \rangle = 3.6$/pulse) and could be substantially raised in a future experiment with a more selective trigger. Neutron fluxes of $\gtrsim 10^8$ per pulse should be readily attainable in our chamber in the P-East beam.

As will be detailed in section III, we believe we will either find B particles or set limits that are both theoretically interesting and experimentally important for designing the next step in the search for hadronic B production. We note here that for $\tau_B = 5 \times 10^{-13}$ sec and 10% semi-leptonic branching ratio we would expect to detect 97 B events per μb of production cross. Even if the B semi-leptonic branching ratio were zero we would still expect $\geq$ 10 events/μb for $\tau_B \geq 5 \times 10^{-13}$ sec and if the B lifetime were zero we would expect to detect 21.5 events/μb if the semi-leptonic branching ratio were 10%. The detailed goals for our study of charm production are given in section IV. We note here only that we will be able to make independent measurements of D-meson lifetimes and semi-leptonic branching ratios.

Given the very impressive record of discovery in charm physics of the e^+-e^- colliding beams machines and the (hopefully) imminent discovery of the "B" mesons at CESR and PETRA, one might question the usefulness of hadronic production for B and charm physics. We believe, however, that quite apart from the interest in the production mechanisms themselves, hadronic production will prove to be an important -- even essential -- tool in the study of the physics of these new particles. Our reasons are very briefly listed below.

1. Rate

   We now know that charm production cross sections at Fermilab energies are $\gtrsim$ 10 μb. B production rates are of course unknown but are likely to be $\gtrsim$ .01 μb. These numbers when combined with available beam fluxes of $\sim 10^6$ and realistic target densities yield production rates which are hundreds of times greater than those available in e^+-e^- colliding beams.

2. "Eclectic" Production

   The intrinsic complexity of hadronic production is very likely to produce significant numbers of all the different types of B and charmed particles including the higher mass resonant states which will decay strongly. On the other hand, e^+-e^- annihilation tends to proceed primarily through a few favored channels. For example, it is only recently that charmed baryon production has been definitively found at SPEAR[1] with a $\sigma \cdot B$ (for decay into the reconstructable final state $Pk^- \pi^+$) of $.037 \pm .012$ nb.

3. Associated production.

   Hadronic production has, with photoproduction (real and virtual) the feature that the net beauty or charm of the system produced is zero. Thus one B particle can be used as the "trigger" to make unbiased studies of the properties of the other, etc. It is this feature which allows us to independently measure the lifetimes and leptonic branching ratios of the D-mesons.

4. Accessibility of the Production and Decay Vertices.

   The ability to "see" the production and decay vertices is obviously essential for the measurement of the lifetimes of the new particles. The knowledge of which final state particles come from the B or charm decay(s) is important for two other reasons as well. First, it is the only way one can study certain features of decays which are not fully reconstructable (e.g. semi-leptonic decays). Secondly, for the reconstructable decays, knowledge of the correct parentage of the final particles greatly reduces the combinatorial background in reconstruction. It is, for example, difficult to imagine extensive studies of the strongly decaying charmed and beauty states without this reduction of combinatorial background.

The outstanding difficulty of hadronic production as a tool in the study of Charm and Beauty is, of course, the fact that the background is large. The Charm and Beauty cross sections are a small fraction ($\sim 10^{-3}$ and 10^{-6} or 10^{-7} respectively) of the total hadronic cross section. It is our belief, that the correct approach to this problem lies in the use of a triggerable, high resolution vertex detector combined with a powerful and sophisticated downstream detector, and that this technique can be developed to the state where the full advantages of hadronic production can be realized.

We are exploring the possibility of a collaboration with a Fermilab group to use the magnetic spectrometer in the broad band photon beam in P-East. The apparatus for the experiment proposed here would be located upstream of the apparatus for E-400 and many of the problems -- moving, neutron beam, and configuration of our electronics -- are common to the proposed experiment and to a future experiment involving the HIRSC and the E-400 apparatus as a powerful downstream spectrometer. At the same time as the proposed experiment would run, it would also be possible to make trigger studies (using a small target simulating the streamer chamber) which would be essential to the design of a future experiment. It is possible that we could also use part of the E-400 apparatus to measure the particles which go through the central aperture of the muon detector.

Preliminary calculations suggest that the E-400 apparatus could be configured so as to provide very selective triggers and almost complete downstream measurements for a wide variety of Charm and Beauty studies. In a complimentary sense, the information we would obtain from the currently proposed experiment -- cross section, lifetimes, semi-leptonic branching ratios (or relevant limits) -- for the B particles would also be important for the design of a subsequent experiment. It is perhaps worth noting that such information, in the preliminary form needed for choosing the most interesting next experiment, could be obtained without a lengthy analysis period.

A program of improvements, funded by Fermilab, DOE, and Yale, to the HIRSC was begun following the E-490 run. A detailed description of the improvements is given in section V. We note here that we will certainly have track widths less than 80 μm (in space) and have excellent prospects for achieving tracks of 50 μm width, the limit of the image tubes used in the current version of the chamber. These represent very substantial gains on our E-490 performance which yielded tracks with 150-200 μm widths. The chamber will be fully tested in our test run this spring in the M1 beam. We also note that it is still strongly limited by the design choices which were made in its initial construction. For example, a minor change in the design of a new chamber -- operation with cold gas (~ liquid N_2 temperatures) -- would result in nearly another factor of two reductions in the intrinsic track width. Similarly, straightforward extensions in the length of the chamber in the beam direction would give large factors in data rate. An active program of development of such chambers is continuing and will be an important aspect of future work of the group which is making the current proposal.

The physics results we propose to obtain depend very strongly on the availability of a toroidal iron magnet with an outside diameter of $\gtrsim$ 5 feet and an inner hole diameter of ≈ 1 ft. A bending strength of 50 kg-m is required. As is discussed in section II, the toroid is essential for the B experiment in that it would provide muon charge, momentum and transverse momentum. Without this information our sensitivity to B production would be seriously limited in the accessible range of B particle properties.

Finally, we comment on the possibility that circumstances may arise which would make it impossible to run in the P-East neutron beam for a time period of such duration that an earlier run in the M1 beam, where the apparatus is now situated, becomes a feasible option. While this is not our first priority, we believe that a modest exposure to a pion beam in M1, with the apparatus supplemented by a downstream toroidal magnet, is amply justified by the physics content of the results. In particular, a comparison of charmed particle production by pions with charm production by nucleons would provide extremely interesting information about the fundamental interaction between quarks. In this sense it would complement the neutron beam exposure which is proposed here and would as well provide additional data for the studies of charmed particle production discussed below.

II. Apparatus and Experimental Method

The apparatus is shown in Figure 1. The collimated neutron beam interacts in the HIRSC and the occurrence of an interaction is detected, as in E-490, by an 8 counter hodoscope located just downstream of the chamber exit window. The improved version of the chamber is described in section V. Muons are detected (for the trigger) by the hodoscopes B, μ, and μ' and by one or more counts in the multiwire proportional chamber downstream of the toroids. Suitable "tracking" coincidences are required of the hodoscope counters to insure consistency with the passage of one or more reasonably (within multiple scattering deflections) straight trajectories through the shield. All scintillators and all counts in the MWPC's are latched and recorded on magnetic tape. The MWPC's, which are described in section V, are new chambers with a spatial resolution of .58 cm (standard deviation).

The B particle and charm particle studies are done simultaneously with the same trigger. The trigger is as described above:

$$\text{Trigger} = B \cdot I \cdot MU \cdot \overline{CV}$$

where B ≡ no counts in hole veto counters around beam

I ≡ 2 or more interaction hodoscope counts

MU ≡ B, μ, μ' and last MWPC coincidence (tracking required for B, μ, μ').

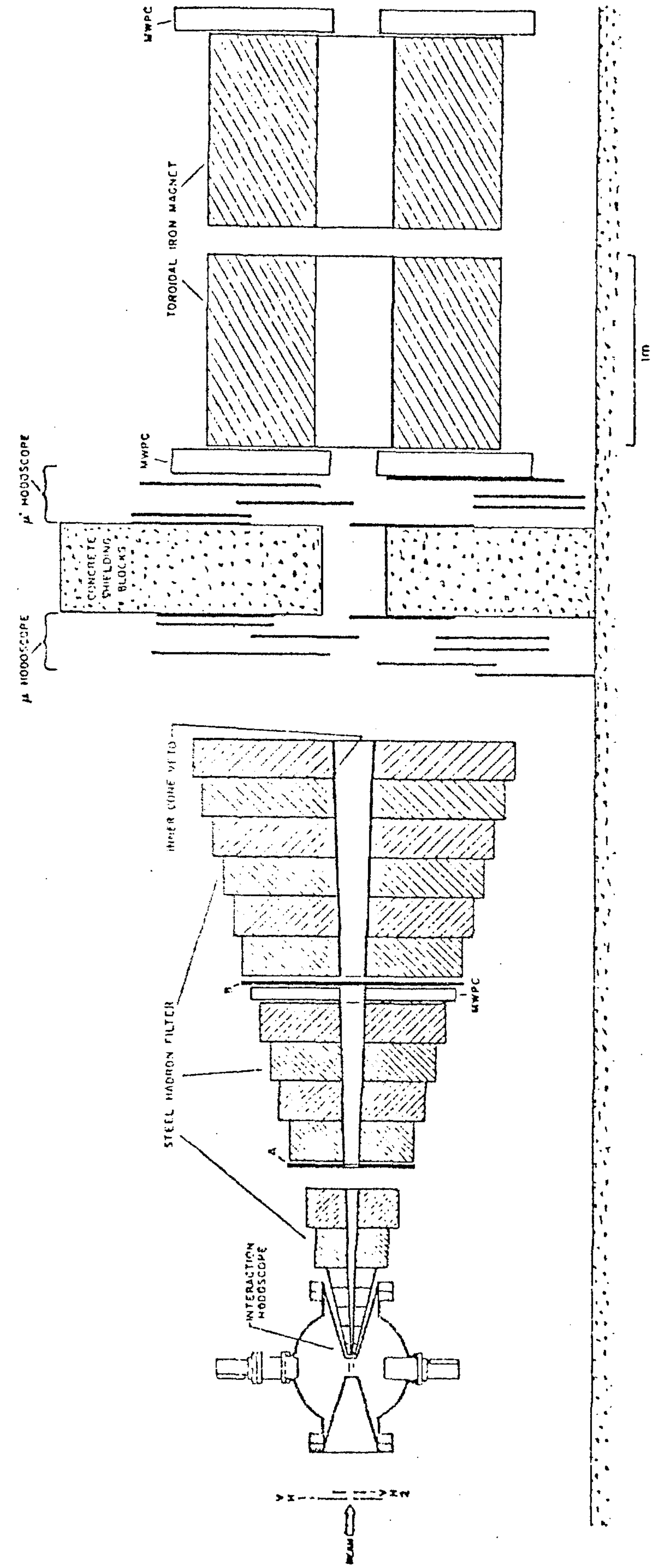
MWPC
TOROIDAL IRON MAGNET
1m
MWPC
μ' HODOSCOPE
CONCRETE SHIELDING BLOCKS
μ HODOSCOPE
INNER CONE VETO
MWPC
STEEL HADRON FILTER
A
INTERACTION HODOSCOPE
BEAM

Figure 1

$\overline{CV}$ ≡ no count in the inner cone veto counter

This trigger, without the toroid, was extensively studied in E-490. We have estimated the reduction in trigger rate due to the additional steel in the toroid to be a factor of 7 from a Monte Carlo calculation. For purposes of estimates in this proposal we have used a somewhat more conservative factor of 5 for the trigger rate reduction due to the toroid. Table I gives the properties of the neutron beam and the relevant trigger rates and picture numbers for the proposed 600 hour run.

Table I

Neutron Beam, Trigger Rates, and Picture Numbers for a 600 Hour Run

Neutron Beam Cross Section	1.5 cm (H) x .1 cm (V)
Neutrons per pulse	3.86×10^7
Number of Triggers per pulse	3.6
Live Time Fraction	.276
Fraction of Fiducial Volume pictures "lost" due to 2nd neutron interaction	10%
Assuming 4 pulses/minute and 20/24 = .833 Beam use Efficiency:	
Total number of pictures	434.4×10^3
Total number of Fiducial Volume pictures	82.5×10^3

In constructing Table I we have used the information from E-490 with the additional assumptions that the toroid steel lowers trigger rates by a factor of 5 and that the chamber will operate at 40 atmospheres rather than at 24 atmospheres.

We note that the principal limiting factor is the dead time caused by the trigger rate. A large part of the trigger rate is, as noted in Table I, due to triggers caused by neutron interactions in the windows or the non-visible regions of the gas. In the present set up only 19% of the triggers will be fiducial volume interactions. We are investigating ways of improving the triggering system so as to enhance fiducial volume interactions. A factor of 2 net increase in good fiducial pictures may be attainable.

III. B Particle Search

We have carried out an analysis of B particle trigger rates using a Monte Carlo calculation which is described in Appendix II. The trigger rates do not depend on the B particle lifetimes but do depend on production cross sections and semi-leptonic branching ratios. Table II gives the number of B production events in the sample (of 82.5×10^3 fiducial pictures) which would be obtained in a 600 hour run.

Table II

B-Particle Event Rates in 600 Hours

Assumed B Semileptonic Branching Ratio	Number of B Events in the pictures of 600 Hour Run
0	254 / μb of B prod.
10%	732 / μb of B prod.

Our basic strategy in searching for the B events is to use the chamber information and the muon detector information in as complete a fashion as possible. The possible signatures for B events are:

1. 3 μ's with or without a secondary vertex.
2. 2 μ's of like sign with or without a secondary vertex.
3. 2 secondary vertices and a μ from the primary vertex.
4. Any event with three or more secondary vertices.
5. Any event with a visible decay chain.

In all of these a μ signifies a muon in the muon detector whose trajectory aligns well with a track measured in the event in the chamber. We note that 1,2, and 3 require a B semi leptonic decay and cannot occur via "simple" charm, anti-charm production. Categories 4 and 5 could also be signatures of τ lepton production, presumably through processes like:

$$
\begin{array}{l}
n + N \rightarrow F^{+} + F^{-} + X \\
\qquad\qquad \hookrightarrow \tau^{+} + \nu_{\tau} \\
\qquad\qquad\qquad \hookrightarrow \mu^{+} + \nu_{\mu} + \bar{\nu}_{\tau}
\end{array}
$$

Since the kinematics of B and F production and decay are rather different it is likely that τ production can be distinguished from B production by a detailed analysis of the event. In many cases the muon measurements (transverse momentum for example) will resolve the issue. In the worst case where τ and B hypotheses both survive, at least the rate for an interesting process which can be studied in a future experiment will have been established.

The Monte Carlo program described in Appendix II has been used to generate B events and has been used to overlap B production and decay tracks on a sample of pictures obtained from the E-490 run. The composite events were then redrawn with our new estimated track width of 50 μm. The resulting sample of events were then scanned by physicists to yield a set of detection efficiencies. The E-490 sample was the sample of charm candidate events which are as "close" to a representative sample of B events as we can obtain at the present time.

For the case of B semi-leptonic branching ratio equal to zero one case, $\tau_B = 5 \times 10^{-13}$ sec, was studied. For the case of the Branching ratio equal to 10% two subsets, $\tau = 5 \times 10^{-13}$ sec and $\tau = 0$ were studied. The results are given in Table III.

Table III

Detected B Particle Events per 600 hour Run

Semi-Leptonic Branching Ratio	B-Particle Lifetime	No. of Detected Events in 600 hr Run
0	5×10^{-13} s	10 events / μb
10%	5×10^{-13} s	97 events / μb
10%	0	21.5 events / μb

In the range 10^{-13}sec to 10^{-12}sec our detection efficiency is approximately a linear function of the B particle lifetime. With this assumption (of a linear dependence of detection efficiency on τ_B) we have constructed figure 2 which shows both the expected number of detected events per μb of B production cross section versus lifetime and also the minimum cross section versus lifetime which would give us 2 events.

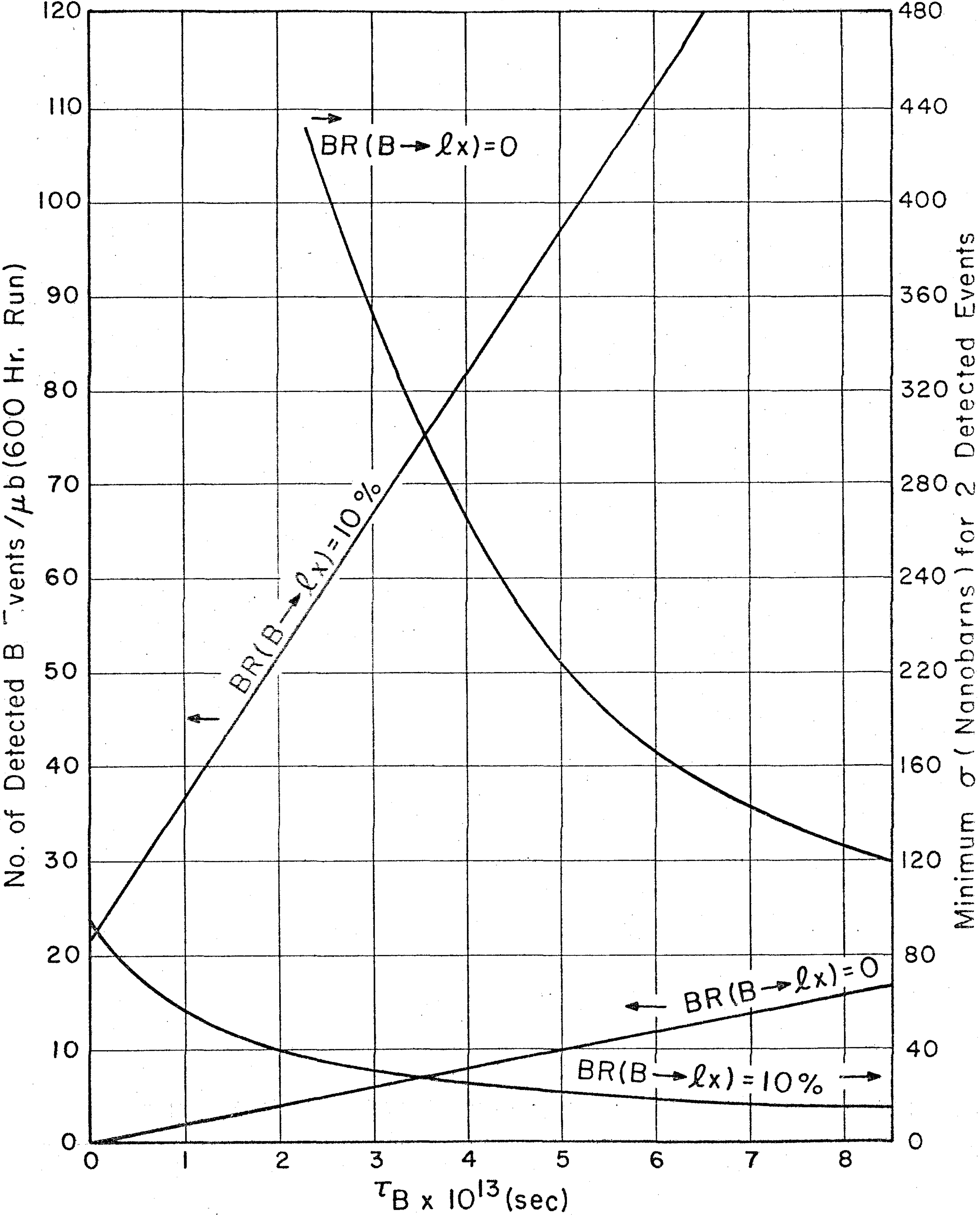
No. of Detected B Events / μb (600 Hr. Run)
Minimum σ (Nanobarns) for 2 Detected Events
BR(B → ℓx)=0
BR(B → ℓx)=10%
BR(B → ℓx)=0
BR(B → ℓx) = 10%
τB x 10^13 (sec)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
110
120
0
40
80
120
160
220
240
280
320
360
400
440
480

Fig. 2

Charmed Particle Production and Decay

The results of the 1978 exposure of the Yale high resolution streamer chamber to a beam of 350 GeV/c protons (Experiment 490) are presented in the attached preprint, submitted for publication to Physical Review Letters. These results demonstrate the capabilities of the system and enable us to predict event rates and trigger rates for the current proposal with considerable confidence. In particular, the demonstration that our trigger design was capable of producing an enhancement factor of between 15 and 50 for events with charmed particle decays into muons, taken together with the Monte Carlo results described below, yields a projected enhancement factor of better than 65 when the addition of a toroidal magnet to the system is taken into account.

a) Event Rates

Assuming a beam flux of 3.86×10^7 neutrons/pulse and using the charm production cross-section of 29 ± 13 μb determined in Experiment 490, we expect about 4.34×10^5 triggers in a 600 hour run, assuming an average pulse rate of 200 per hour over the run. This estimate takes into account the fact that at this beam flux the chamber is sensitive approximately 28% of the time. Since the fraction of these interactions which occur within our fiducial volume is 0.19 and of these some 10% are lost due to multiple interactions, we expect to obtain a sample of approximately 74,280 analyzable pictures. Using the measured charm and total cross-sections as well as the trigger enhancement factor we estimate that of these some 4308 will actually represent charmed particle production.

Using our Monte Carlo program we have generated simulated events with the expected track widths and track backgrounds for such events. Applying our usual scanning techniques we can then estimate our scanning efficiency for the detection of charmed particle production and decay as 44%, which yields a final sample of 1896 events on which to draw for determinations of cross-sections, branching ratios and lifetimes of charmed particles.

b) Lifetimes and Branching Ratios

In order to demonstrate that the expected sample of detected charmed particle events will permit an accurate measurement of the lifetimes of both charged and neutral D mesons, we have generated a like-sized sample of events using our Monte Carlo production model and assuming lifetimes of 5×10^{-13} sec for $D^{\pm}$ and 0.86×10^{-13} sec for D^{o} and $\bar{D}^{o}$. These events have been analyzed using the overly simplified but statistically correct assumption that the velocity of a massive particle decaying into a relativistic particle at a laboratory polar angle θ is given by

$$\beta = \cos \theta$$

While momentum analysis of the $\mu^{\pm}$ with a toroidal magnet together with consideration of the expected decay spectrum of the D meson will permit us to refine this algorithm considerably, this preliminary analysis should given an indication of the limitations and capabilities of the streamer chamber in determining the D lifetime.

Since we expect our sample to contain at least two lifetimes, a cut was made at a decay length of 2.86 mm, and decay lengths greater than this were analyzed for a single lifetime. Using this result, the data for lengths smaller than the cut-off were then analyzed for a second lifetime. Since the systematic biases of the method were not, as yet, extracted, both lifetime estimates exceeded the input values by about 50%. However, the ratio obtained by this straightforward first approach is accurate to better than 15% and it should be possible to improve both the absolute and relative measurements substantially with a more complete analysis.

The cleanest method of measuring the semi-leptonic (muonic) branching ratios of charged and neutral D mesons independently of each other and independently of the lifetimes is to obtain a sample of clearly visible charged (or neutral) decay vertices which would have been detected independently of the decay mode at that vertex. By scanning simulated charmed production and decay events generated by our Monte Carlo, we have determined that approximately 14% of all $D^{\pm}$ decay vertices and approximately 3% of all D^{o} vertices will be clearly visible. Further, about 68% of these $D^{\pm}$ and 70% of these D^{o} will be produced along with a charged D. Combining these results with the Monte Carlo predictions for the charge configurations in D, $\bar{D}$ pair production yields the results presented in Table IV. While these numbers are not large, they should make it possible to extract values for the branching ratios with about 30% statistical uncertainties.

Table IV

Total No. of charmed events detected in a 600 hour run	1896
No. of $D^{\pm}$ decays with clearly visible vertices	354
No. of D^{o},$\bar{D}^{o}$ decays with clearly visible vertices	35
No of $D^{\pm}$ decays with clearly visible vertices where a μ which would have triggered is from the associated charmed particle	120
No. of D^{o},$\bar{D}^{o}$ decays with clearly visible vertices where a μ which would have triggered is from the associated charmed particle	25

Somewhat larger samples, but with larger systematic uncertainties, may be obtained if one asks only for a sample of events in which the charmed particle decay would have been detected, but not necessarily seen with sufficient clarity to separate neutral from charged D's, whether or not the decay produced a μ. Out of our projected sample of 1896 detected charm decays we expect 571 $D^{\pm}$ and 142 D^{o} to satisfy these criteria. This sample of events should yield an accurate value for the overall branching ratio and, if analyzed in conjunction with the lifetime distribution, should allow us to determine differences in the branching ratios of neutral and charged D mesons if their lifetimes are, as expected, substantially different.

Independent measurements of branching ratios and lifetimes of D mesons constitute a crucial test of the GIM theory[2] of charmed particle decays. According to this theory, the "Cabibbo allowed" part of the charmed quark decay into the strange quark has $\Delta I = 0$ and therefore the inclusive semileptonic rates for D^{+} and D^{o} are equal up to corrections of the order of $\tan^2\theta_c = 0.05$, i.e.:

$$\Gamma_{\ell}(D^{+} \rightarrow \ell^{+} + \nu_{\ell} + \bar{K} + \ldots) = \Gamma_{\ell}(D^{o} \rightarrow \ell^{+} + \nu_{\ell} + \bar{K} + \ldots)$$

where $\ell^{+} = \mu^{+}$ or e^{+}. As pointed out by Pais and Treiman,[3] this implies that the ratio of the semi leptonic branching ratios must be equal to the ratio of the lifetimes, i.e.:

$$B_{\ell}(D^{o})/B_{\ell}(D^{+}) = \Gamma(D^{+})/\Gamma(D^{o})$$

Previous lifetimes determinations (other than in emulsion) have been based on this assumption, but no other independent test of its validity has been carried out.

Aside from this fundamental check of the theory, there is considerable theoretical interest in the charged D and neutral D lifetimes (and branching ratios). Differences in these lifetimes are not consistent with the assumption that the decay of the charmed quark occurs independently of the $\bar{d}$ (or $\bar{u}$) quark within the D meson and hence an accurate measurement of this difference will provide a sensitive test of theoretical models of the interaction between strange and non-strange quarks.

c) Charmed Particle Production

With the branching ratios derived from our proposed experiment it will be possible to determine the production cross-sections and Feynman x distributions for D mesons in hadron-hadron collisions. These measurements will be crucial, not only for the design of future experiments, but for an eventual understanding of the strong interaction. Although we have not attempted to estimate rates, it is also possible that we will be able to determine production cross sections for $F^{\pm}$ mesons and charmed hyperons (i.e. Λ_c^+) to a useful level of accuracy. In particular, if the lifetime of the $F^{\pm}$ is ~30% of the lifetime of the $D^{\pm}$, as is indicated by preliminary experiments, this signal should be detectable in our decay length distribution for charged charmed particles.

V. Experimental Developments

A. Streamer Chamber Improvements

Following our E-490 run, we have carried on a program of improvements to the chamber. These improvements are of two general types. First, the E-490 run served as a life and reliability test for the chamber system. The outstanding weak link was the Marx generator which was borrowed from an old Fermilab 30" bubble chamber, wide gap chamber, hybrid experiment. Another serious limitation was the performance of one of the two image intensifier tubes used in the optical system. Both tubes were purchased as "factory rejects" (at ½ price). As it developed, one tube had excellent properties including an optical gain of 10,000 but the second tube had a maximum gain of 2500 which necessitated (for stereo) the operation of both tubes at 2500. At this low gain, there is some production of flares at the interaction vertex (in about 30% of the events).

In addition to improvements to the chamber reliability we are also carrying out a fundamental improvement to the chamber high voltage pulsing system. We will use a high power pulsed Nitrogen laser (split into four beams) to synchronously trigger the four spark gaps of the Blumlein pulse forming system. This should allow operation at a voltage of 300 kV which is twice the value previously obtained and which in turn will allow operation at twice the pressure used in E-490 (i.e. we should operate at $\geq$ 40 atmospheres instead of 24 atmospheres).

The individual streamers in our previous run were ~50 μm in diameter With twice the pressure they would be ~35 μm if we operated at the same optical gain (2500). With the new tubes, optical gain of ~15,000 is guaranteed so the individual streamers will be less bright, and smaller than 35 μm. The observed track width of 150 μm was due to thermal diffusion of the initial ionization electrons during the H.V. delay. Reducing the delay from 750 ns to 450 ns will reduce this diffusion by a factor $\sqrt{\frac{750}{450}} = 1.29$ and doubling the pressure will reduce it by a factor $\sqrt{2} = 1.414$ for an estimated track width of 82 μm. The addition of ~1% Xe would change the effective diffusion constant by approximately a factor of 5 which would produce diffusion widths of 37 μm. It is thus reasonable to expect tracks of intrinsic width ~50 μm which we know are clearly visible with our image tubes (although close to their limit).

We summarize the status of these improvements in the section below.

1. Marx Generator - a new Marx generator with 400 kV maximum output and 150 ns total delay has been purchased from Pulsar Associates. The generator has been delivered to Yale and has performed as expected. The short time delay of the new Marx will allow us to shorten our total delay between the logic trigger and the appearance of the high voltage pulse at the chamber by 300 ns. Since as noted above the dominant limiting factor in the track width and chamber resolution is thermal diffusion of the seed electrons during the H.V. delay time, this should result in substantially improved resolution.

2. New Image Tubes.

   We have ordered two new image tubes with full specification properties. The tubes which are scheduled for delivery in March are physically identical to our present tubes and will be easily substituted in the optical system. The one good, half price tube, will then serve as a spare.

3. Laser Triggered Blumlein.

   A 1 MW peak power nitrogen laser has been purchased from NRG, Inc. and has been delivered to Yale. The laser has been extensively tested and the various instrumentation needed for operating, monitoring and manipulating the laser beams has been acquired and exercised. A prototype Blumlein electrically equivalent to our chamber, has been constructed and is just beginning to be used in a test program to optimize the parameters for laser triggering. On the basis of this experience we will choose the precise form of the mirror modification needed to adapt our chamber to laser triggering.

The improved chamber will be operated in the M1 beam during the spring 1980 running period and will be fully tested before its use in the experiment proposed herewith. As also noted above, during these tests we will evaluate the use of a small admixture of Xe.

B. New Multiwire Proportional Chambers.

The MWPC's are new chambers with cathode readout so that 3 coordinates (x,y,u) are read out in each chamber. The wires are wound with 2 mm spacing and the cathode strips are 5 mm wide, however both wires and cathode strips are grouped (outputs electronically added together) in segments that correspond to 2 cm wire spacing. The spatial resolution of the chambers is then $2/\sqrt{12}$ cm = .58 cm (standard deviation) which is more than adequate for the current experiment. In a future experiment the resolution of the chambers could be improved greatly by adding more readout electronics and reading individual wires and cathode strips.

The design of the chambers has been tested with a prototype which was full scale in all important dimensions. The chambers are currently under construction and will be available for testing in our spring 1980 test run in the M1 beam. We note that except for a preamplifier stage for the cathode readout (which was tested with the chamber prototype) these chambers use the same read out design which was developed and tested for our work on E-497.

C. New Film Analysis System

1) Scanning and Pre-digitizing

Film from the 1978 high resolution streamer chamber exposure was scanned and measured on image plane projectors which had been designed and constructed more than fifteen years earlier. While the theoretical accuracy of these machines is approximately 10 μm, maintaining this level of performance with obsolescent electronics and a vintage control computer (a PDP 1) has become increasingly time consuming. During the past six months, therefore, we have acquired three film analyses machines on long term loan: a Vanguard film plane digitizer from Indiana University, with a least count of 2.5 μm, and two image plane digitizers from Argonne National Laboratory, with least counts of approximately 8 μm. These machines will shortly be interfaced to an LSI-11 computer which will control the calibration and data acquisition. The LSI-11 programs, in contrast to the previous system at Yale, are being written almost entirely in FORTRAN and will thus be readily upgraded and adapted to new experiments. Further, the new system will permit precise and automatic film advance, a feature which will substantially improve our scanning rates. Current projections of the performance of these machines indicate a scanning and pre-digitizing rate of at least 600 events per day.

New Film Analysis System (cont'd.)

2) Measurements of the events from the 1978 run were performed entirely on the previous image plane digitizer at Yale (least count ~ 10μm). While the inherent accuracy of these machines was adequately matched to the track image width of approximately 150 μm, considerably higher accuracy will be required to extract the maximum possible accuracy from tracks of 50 μm width. It is planned therefore to measure the new film on the Yale PEPR system which is capable of measuring to a precision of approximately 2 μm.

Since PEPR is designed and optimized to measure bubble chamber track images, it is important to test the feasibility of using this system on streamer chamber track images which may have larger widths and less well defined profiles on films. Accordingly, film from the 1978 run was mounted on the SAMM measuring system at FNAL and new data obtained in a variety of background situations was examined. Results from this study were sufficiently encouraging to warrant major modifications of the Yale PEPR system in order to approximate the SAMM method of measurement. These modifications have now been completed and are currently being tested. It is estimated that the precision measuring rate on PEPR will be approximately one event per minute.

Using the new film analysis system at Yale it should be possible to handle an exposure of 434,000 frames with 82,500 measurable events in a period of approximately six months.

APPENDIX I: CHARM MONTE CARLO

We have written a Monte Carlo program to model our apparatus in order to calculate the various detection efficientices quoted above. The program is written in three independent segments; event generation, trigger, and scan efficiency. All the model dependent physics input is contained in the event generator, the other two program segments are identical for the charm Monte Carlo discussed here and the beauty Monte Carlo discussed in Appendix II.

Event generation

Charm particles are produced using an independent particle prouction model, parameterized as follows:

$$\frac{d^2\sigma}{dXdP_\perp^2} \propto e^{-[AP_\perp + BX^2]} . \qquad A = 2.08\ \mathrm{GeV}^{-1} \quad B = 9.94$$

where X and $P_\perp$ refer to each charmed particle independently. We have also tried a correlated production model[4] :

$$\frac{d^2\sigma}{dXdP_\perp^2} \propto e^{-AP_\perp} [1-|X|]^B \qquad A = 2.08\ \mathrm{GeV}^{-1} \quad B = 9.94$$

$$\frac{d\sigma}{dM} = M^{-\alpha} e^{-\beta M} \qquad \alpha = 3.0 \quad \beta = 0.55\ \mathrm{GeV}^{-1}$$

where X and P are the kinematic variables of a mass M which decays isotropically in its center of mass into a pair of charmed particles. The mass distribution is as given above. We observe no significant difference between these two models with our apparatus and choose to adopt the former for simplicity. All charmed particles produced are considered to be D mesons. The four possible charge states D^+D^-, $D^+\bar{D}^0$, D^0D^-, $D^0\bar{D}^0$ are produced with equal probability.

Charmed particle decays are parameterized by seperate semileptonic branching ratios and lifetimes for neutral and charged D meson given in the Table below:

	B_ℓ	τ ($\times 10^{-13}$ sec)
$D^\pm$	23%	5.0
$D^0, \bar{D}^0$	4%	0.86

The semileptonic decay modes allowed are $D \to K\ell\nu_\ell$, $D \to K^*\ell\nu_\ell$, where ℓ is either e or μ, with equal semileptonic branching ratios. The hadronic decay modes are $D \to K\pi + m(\pi)$ with m poisson distributed with a mean $\langle m \rangle = 1.7$ and the mean charged multipicity constrained to be $\langle m_{ch} \rangle = 2.3$ for both D^0 and $D^\pm$ decays. All decay distributions are isotropic and given by phase space.

All events are generated but only those with at least one muon in the final state with $E_\mu > 3.0$ GeV and $30\text{mR} < \theta_\mu < 250\text{mR}$ are kept for further consideration.

Trigger

Each muon in an event is tracked through the apparatus to determine whether it satisfies the trigger requirements. In order to trigger, a muon most satisfy the tracking requirements imposed upon the three scintillation counter hodoscopes and reach the last MWPC behind the toroidal magnets. Any muon which leaves the iron shield, either outside, or in the hole is considered lost. The minimum range requirement for a trigger muon is ~7.0 GeV.

Muon tracking is done using the full dE/dX and multiple scattering formalism.

Events which have at least one trigger muon are sorted out and saved to make distributions, etc.

Scanning efficiency

The procedure described above makes no attempt to model any products of the primary interaction except for charmed particles. The correction to the trigger efficiency due to this has been measured in our previous run and is applied straight-forwardly to the results obtained above. In scanning the film however, the most significant effect which causes downstream decays to go undetected is the obscuration due to the superposition of tracks from the primary vertex over tracks from the decay.

In order to estimate our scanning efficiency for various types of events we have measured a sample of events from our previous run, tabulating for each event the angle of all tracks which appear to come from the primary vertex. A picture is then drawn of one of these events superposed upon one of the Monte Carlo events which satisfied the trigger requirements. Each track is drawn with a width corresponding to our expected resolution of 50μm. These pictures are then scanned by a physicist to determine the scanning efficiency.

Shown in Figure A-1 is an example of this procedure. Notice that the fourth track from the bottom kinks about 3mm downstream of the primary vertex. This event represents a clearly identified charged D decay. Figure A-1 is drawn with 50μm wide tracks corresponding to our expected resolution. For comparison the same picture is drawn with 175μm track width in Figure A-2. This corresponds to our previous run with the streamer chabmer. This particular event is undetectable with the old resolution.

APPENDIX II: BEAUTY MONTE CARLO

Event generation

In order to model the production of praticles with beauty we have used exactly the same independent particle production model used to produce charm and described in Appendix I. The parameters used are the same as in the charm case, the only difference being that the particle produced is assumed to have a mass $M_B = 5.2$ GeV/c^2.

The particles produced are assumed to be charged and neutral mesons $B^{\pm}$ and $B^0(\bar{B}^0)$ respectively. The decay scheme we have modeled assumes a $\Delta B/\Delta Q=+1$ rule; that is $B^- \to D^0 + X^-$ and $B^0 \to D^+ + X^0$. The semileptonic branching ratio is assumed the same for $B^{\pm}$ and $B^0(\bar{B}^0)$. Two cases have been run $B_\ell = 10\%$ and $B_\ell = 0$. The mass of the B is sufficiently high that τ semileptonic decay is assumed to proceed at the same rate as μ or e. The semileptonic branching ratio of the tau is taken as $B_\mu^\tau = 17\%$ and the hadronic τ decays are modeled in accordance with the world's τ data. Hadronic B decay modes are $B \to D\pi + m\ (\pi)$ and the same algorithm is used as was used for charm decay. The lifetime of the B is taken as $\tau_B = 5 \times 10^{-13}$ sec for both $B^{\pm}$ and $B^0(\bar{B}^0)$, and in a separate calculation, $\tau_B=0$.

Trigger

The trigger requirements are exactly the same as for the charm case. It is worth noting that as many as four muons might be produced in the decay chain of a $B\bar{B}$ pair. Particularly the like sign dimuon, trimuon and four muon final states cannot arise from charm decay. While the requirement that we identify a muon and determine its sign is basically the trigger requirement $E_\mu > 7.0$ GeV, $30\text{mR} < \theta_\mu < 250\text{mR}$; muons in the same angular range with $4.5\text{GeV} < E_\mu < 7.0\text{GeV}$ will be known to be muons, although their signs are not determined.

Scanning efficiency

The scanning efficiency is determined using the same technique as was used for the charm Monte Carlo.

In Figure A-3 we show a couplete $B\bar{B}$ event. The vertical scale is expanded by a factor 10 in order to separate particles. Notice that the D^- is sufficiently energetic (E_{D^-} = 102GeV) that it leaves the chamber without decaying (20mm flight path). Figure A-4 shows the same event as it would appear to a scanner.

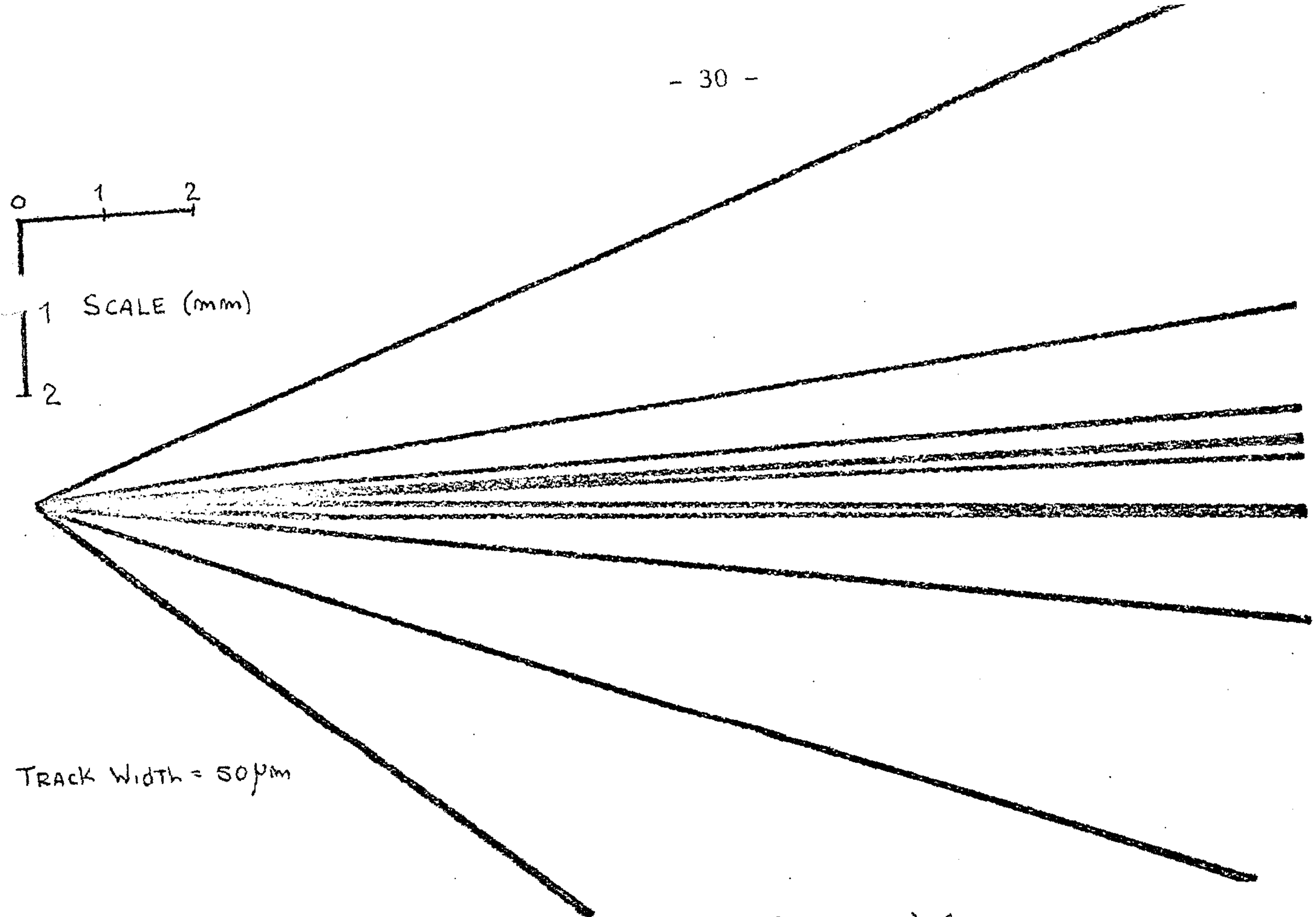

FIGURE A-1

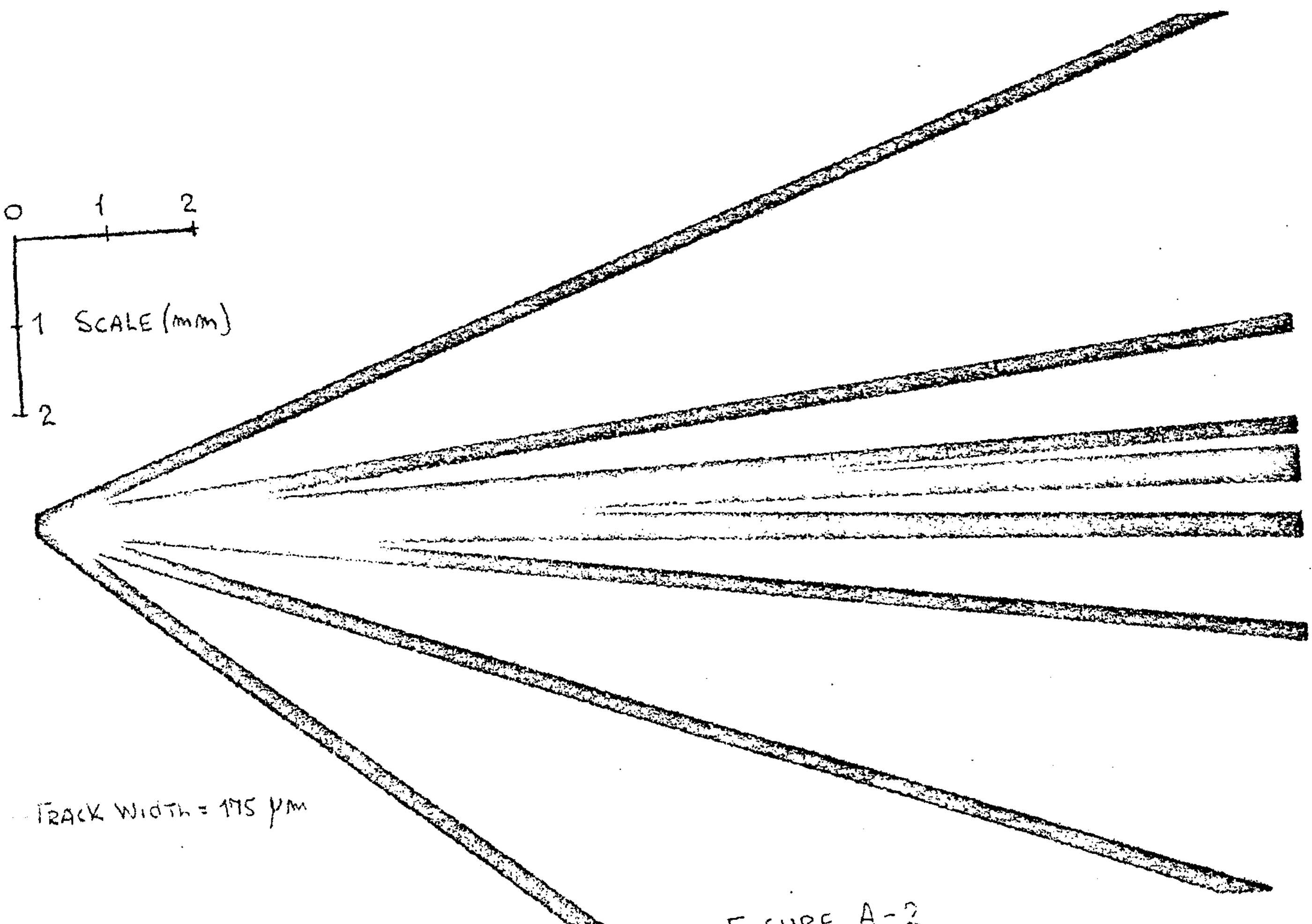

FIGURE A-2

$$B^0 \longrightarrow D^+ \mu^- \bar{\nu}_\mu$$
$$\quad \hookrightarrow K^- \pi^+ \pi^+ \pi^0 \pi^0$$
$$\bar{B}^0 \longrightarrow D^- \pi^+ \pi^0$$

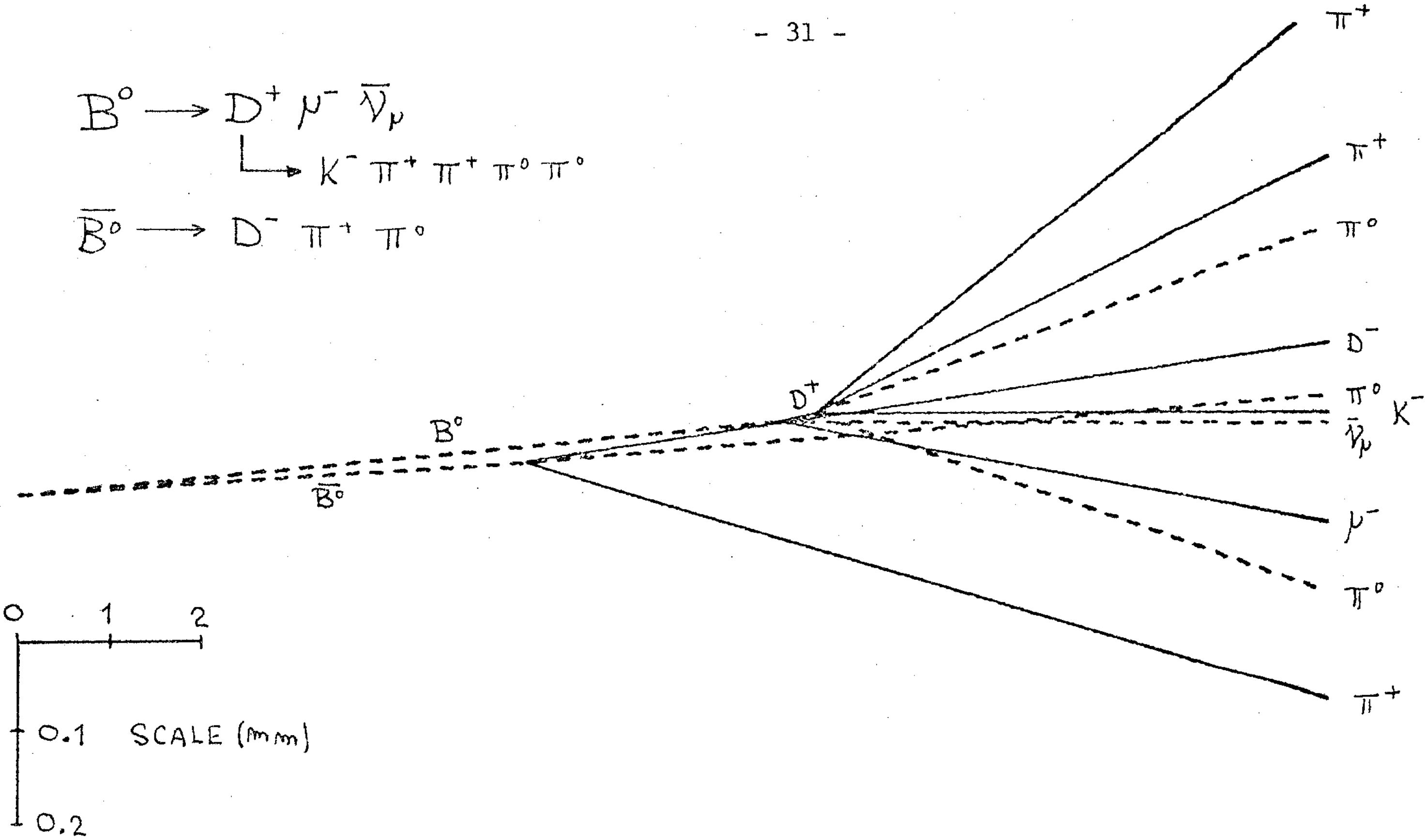

FIGURE A-3

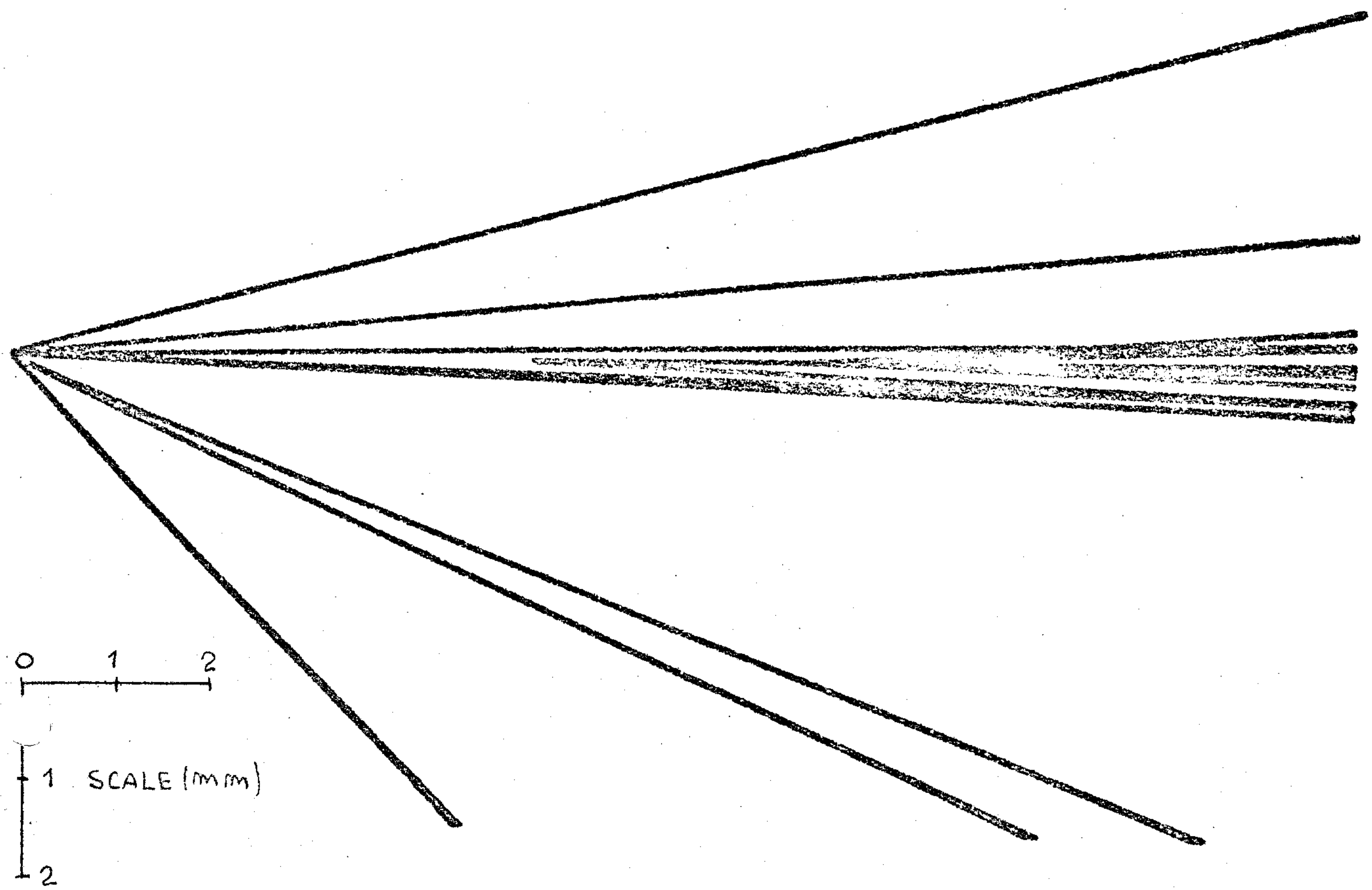

FIGURE A-4

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Appendix to 630

OBSERVATION OF HADRONIC CHARM PRODUCTION IN A HIGH RESOLUTION STREAMER CHAMBER EXPERIMENT†

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Abstract

Short lived particles produced in association with muons have been observed in the interactions of 350 GeV/c protons with Neon in a high resolution streamer chamber. The production and decay of these particles are consistent with the known characteristics of charmed particles and the average lifetimes must lie between 10^{-13} and 2×10^{-12} seconds. Assuming that the events are mainly $D^{\pm}$ mesons with lifetimes of approximately 10^{-12} seconds, the production cross section is estimated to lie between 20 μb and 50 μb per nucleon.

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⨍ Currently at University of Maryland
≠ Currently at Fermi National Accelerator Laboratory
Currently at Brookhaven National Laboratory
* Currently at Lawrence Berkeley Laboratory
** Currently at CERN
*** Currently at Stanford Linear Accelerator Center

The discovery of particles with the theoretically predicted attribute of charm as well as the theoretical prediction that charmed particles should have lifetimes of the order of 10^{-13} seconds [1,2,3] have motivated a number of experiments to observe directly the decays of such particles.[4,5,6,] Several of these experiments, in particular those using bubble chamber and emulsion techniques,[7,8] have observed such decays associated with neutrino interactions. The experiment reported here was designed to detect the production and decay of charmed particles in hadronically induced events where the production rate is perhaps as low as 0.1% of the total interaction rate. For hadronic production of charm, therefore, it is advantageous to employ a device which is triggerable with fast electronics yet retains the capability of recording short decay lengths.

A high resolution streamer chamber has been developed and used to study production of charmed particles by incident 350 GeV protons interacting with the nuclei of the chamber gas consisting of 90% Ne and 10% He at a pressure of 24 atmospheres. The chamber has been described elsewhere[9] and we present here only a summary of its properties as shown in Table I.

Table I Streamer Chamber Parameters

Gas	90% Ne, 10% He @ 24 atmosphere
Electric field	333 kV/cm
Pulse width	.5 ns
Image intensifier	ITT Model F4112, optical gain 2500
Gap height	.45 cm
Length of visible region in beam direction	4.0 cm (Fiducial Region 3.0 cm)
Width of visible region	3.0 cm
Streamer diameter	50 μm
Track width in space	150-200 μm
Precision of measurement of track coordinates	40 μm (in space)

The position of the chamber and the associated muon filter is shown in Figure 1. The experiment was set up in the M-1 beam line at FNAL tuned to 350 GeV positive particles and consisting primarily of protons. The beam was defined by the small counter B1. Upstream interactions were vetoed by requiring that the hole counters VH1 and VH2 not count for a good beam particle. The counter B2, which covered the full aperture of the entrance window assembly (about 3 cm x 3 cm), was used to reject interactions in B1 by requiring an output pulse height consistent with the traversal of a single minimum ionizing particle. Interactions of the incident beam particles in the chamber gas (or windows) were detected by requiring 2 or more counts in a small eight counter hodoscope located just behind the exit beam window. The trigger was designed to select events with prompt muons by requiring, in addition to a beam particle and interaction signal, a count in one or more of the counters behind the muon filter and the absence of a count in the inner cone veto counter. For background studies, some data were also taken with an interaction trigger which required only a beam particle, an interaction and no inner cone veto. Table II summarizes the data sample obtained.

Table II Data Sample

Incident beam	350 GeV protons
Incident flux per pulse	(.5 to .8) x 10^6
Average number of triggers per pulse	~ 1
Number of fiducial interactions with full muon trigger	1062
Number of fiducial interactions with interaction trigger	255
Ratio of non fiducial to fiducial triggers	10/1

The scaled, ungated rates for beam, interaction and muon triggers imply that the muon requirement rejects all but 1 in 2200 hadronic interactions and, if hadrons accompanying charm production are distributed in a manner similar to those produced in ordinary hadronic interactions, that approximately 27% of charm production events survive the cone veto requirement. Using these rates, a Monte Carlo analysis discussed below using different assumptions for charmed particle semi-leptonic branching ratios and lifetimes indicates that the muon trigger events obtained are between 15 and 50 times richer in charm production than a similar sample of "raw" interaction trigger events. Each fiducial interaction was measured on an image plane digitizing system with a resolution (in space) of 12 μm. Events in which one or more tracks clearly did not originate at the primary (production) vertex made up the final sample which was analyzed as follows.

Because of the "large" track width, 150-200 μm, this experiment is primarily sensitive only to those decay tracks which have the largest angle relative to the incident beam direction. It is therefore convenient to analyze the data sample in terms of an ℓ, θ_D plot. The distance ℓ is the distance in space (neglecting dip angles) which the charmed particle traveled before decaying and θ_D is the projected angle of the decay track. When the line of flight of the charmed particle cannot be observed it is assumed to be along the beam direction. These definitions are illustrated in figure 2. The boundary separating the "charm" region and the "strange particle" region was chosen so that for charmed particle lifetimes of 10^{-12} sec. or less there should be a negligible number of charmed particle decays in the strange particle region. It is important to note that this boundary is determined solely by kinematics and does not depend on assumptions about the dynamics of hadronic charm production. Finally, a requirement is imposed on all but the "short decay" events that the projected production angle of the decaying track be within 13^o of the incident beam direction if the event is to be considered a charm candidate. This rejects many strange particle events but very few if any charm events, since at $\theta = 13^o$, $P_\perp = 5.9$ GeV/c for a D meson with $X_F = 0$.

Figure 2 presents the data from the muon trigger sample and shows that there are 10 charm candidate events. The sources of background in this sample include delta rays, secondary interactions and strange particle decays. While delta rays can be shown to give a negligible contribution and secondary interactions amount to less than 0.2 background events, strange particle decays are a potentially serious source of background. From the events observed in the strange particle region, the strange particle decay contributions for those strange particles with momenta less than about 2 GeV/c can be directly estimated. Above 2 GeV/c, where at typical decay angles the potential path for decay of these particles is largely inside the charm region, the background has been estimated using data from a bubble chamber study of 205 GeV/c π^- on hydrogen.[10] The bubble chamber data is also in good agreement with the number of events in the strange particle region of the ℓ,θ_D plot. In carrying out the estimates of the fast strange particle and interaction background certain simplifying assumptions have been made which have the effect of overestimating the background. A summary of the charm signal statistics is given in Table III. It should be noted that, based on the scintillator latches, for two of the charm candidate events the decay track is the only track which could have been the trigger muon. In two other charm candidate events the decay track was possibly but not uniquely a muon.

Table III Charm Signal Summary

Trigger category	Strange particle events	Charm candidates
Muon trigger	26	10
Interaction trigger	8	1

Backgrounds to charm candidates

	Muon trigger	Interaction trigger
"Slow" strange particles	1.07 ± .38	.26 ± .09
Fast strange particles	.85	.20
Secondary interactions	.18	.04
Total	2.1 ± .4	.5 ± .1

This experiment has observed a definite signal in the muon trigger events which cannot be explained by background. While the experiment cannot of itself prove that this signal is due to charm production, the muon association and the lifetime range involved made this a reasonable and self consistent conclusion. In order to extract the charmed production cross-section and lifetime, the net detection efficiency was determined for a particular production model and for two different decay models applied to a Monte Carlo sample generated from the observed events.

The charm production model which was used assumed that D, $\bar{D}$ pairs were produced in an uncorrelated fashion with the following Feynman X (X_F) and transverse momentum ($P_\perp$) dependence.

$$\frac{d^2\sigma}{d(P_\perp{}^2)dX_F} = Ae^{-9.94X_F{}^2 - 2P_\perp}$$

The results are essentially unchanged if an X_F distribution of the form $(1-X_F)^{2.9}$ is used as suggested by studies of prompt single muons.[11] Similarly, including a correlation term of the form[11]

$$M^3 \frac{d\sigma}{dM} \sim e^{-.55M}$$

where M = effective mass of the D, $\bar{D}$ pair in GeV, has little effect on the results since, with the resolution of this experiment, essentially only one of the charmed particles was detected. It is also assumed that the states D^+D^-, $D^+\bar{D}^o$, $D^o\bar{D}^o$ and D^oD^- are produced with equal probability and that the purely hadronic decays of the D mesons proceed via phase space with the multiplicities adjusted so that the average number of charged decay particles from both charged and neutral D mesons is 2.3. Finally, the following two models have been used for the semi-leptonic branching ratios and the ratio of D^o to $D^\pm$ lifetimes:[12]

Model 1: $BR(D^o) = BR(D^\pm) = 10\%$; $\tau(D^o) = \tau(D^+)$

Model 2: $BR(D^+) = 23\%$; $BR(D^o)$ 0%; $\tau(D^o) = \tau(D^+)/5.8$

The use of 0% for $BR(D^o)$ rather than the ~ 4% required by the theory of charm decays is for computational simplicity and is not significant at the level of statistics in this experiment. Assuming that charm events are lost because of the cone veto requirement at the same rate as ordinary hadronic events, the efficiency of this experiment for detecting charm decays as determined by the Monte Carlo program above together with the measured rejection factor for ordinary hadronic interactions determine an enhancement factor F for muon trigger selected events. The charm production cross section is then given by

$$\sigma_c = 30\text{mb} \times \left(N_{charm} / F N_{total} \right)$$

where N_{charm} is the number of charm events observed and N_{total} is the total number of interactions observed.

The results of this analysis are shown in Figure 3. Points are shown for the two models discussed above as well as for Monte Carlo calculations assuming two lifetimes for the $D^{\pm}$, namely 5×10^{-13} sec. and 10^{-12} sec. In this general region the relationship between production cross section and assumed lifetime yielding the observed signal is approximately linear as indicated. Limits on the lifetime may be deduced by noting that if the lifetime were less than 10^{-13} sec the observed events would have clustered at the lowest values of ℓ and θ_D permitted by the scanning efficiency. On the other hand, if the lifetime were greater than 2×10^{-12} sec. the method of background determination used would have eliminated the signal in the charm region.

In conclusion, short lived particles produced in association with muons in hadronic interactions have been observed in this experiment. The most reasonable interpretation is that of charmed particle production. The average lifetime of the particles observed above the strange particle background must lie between 10^{-13} and 2×10^{-12} seconds. If as suggested by references (11) and (12), the lifetime of the $D^{\pm}$ is approximately 10^{-12} seconds, the production cross section is estimated to lie between 20 and 50 μb per nucleon for 350 GeV incident protons.

The development and utilization of the High Resolution Streamer Chamber would not have been possible without the skill and dedication of many people. We are especially appreciative of the support and assistance of the research division and meson laboratory division of FNAL in the entire process of building the chamber and setting up and running the experiment.

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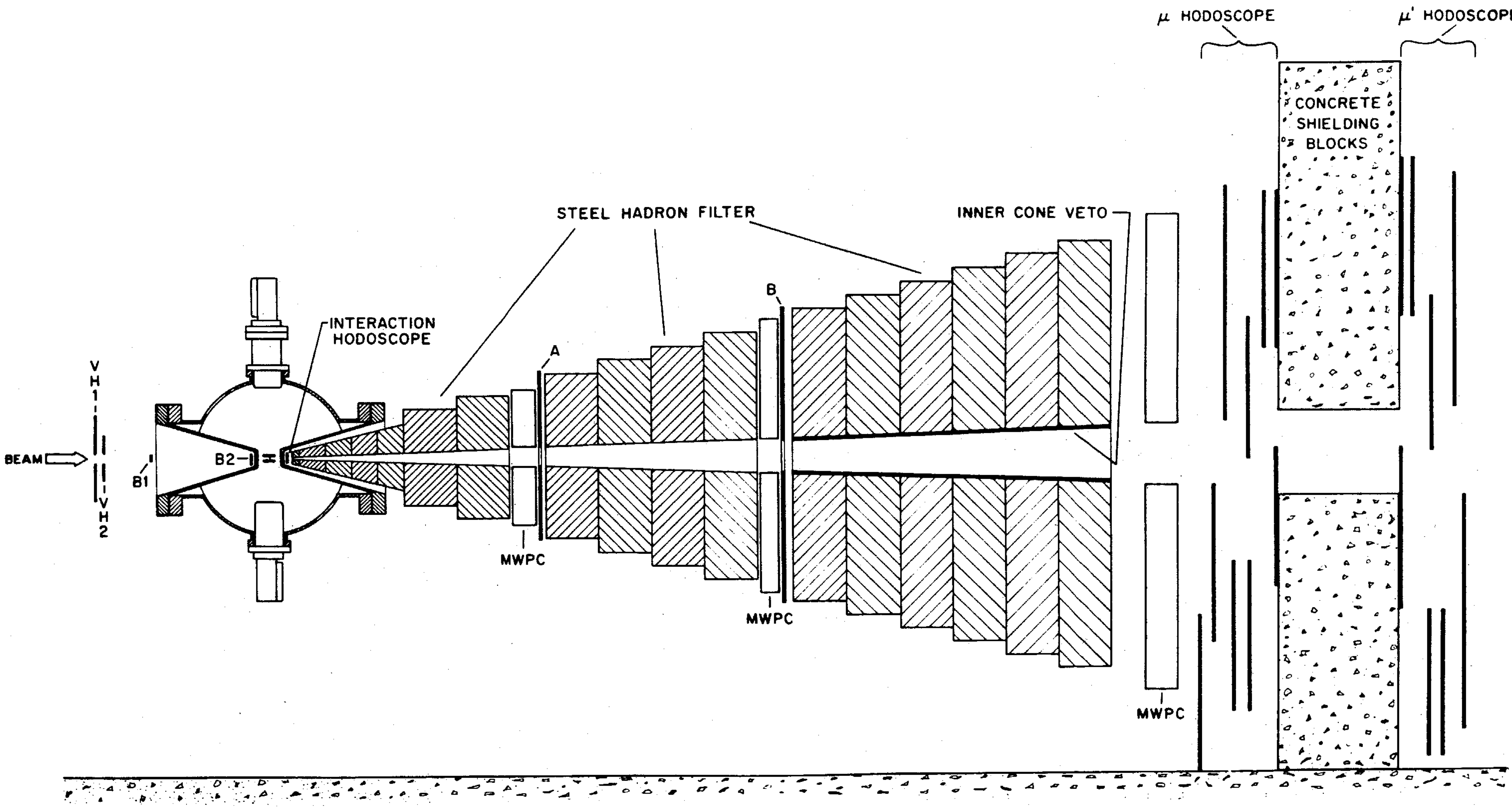
Figure Captions

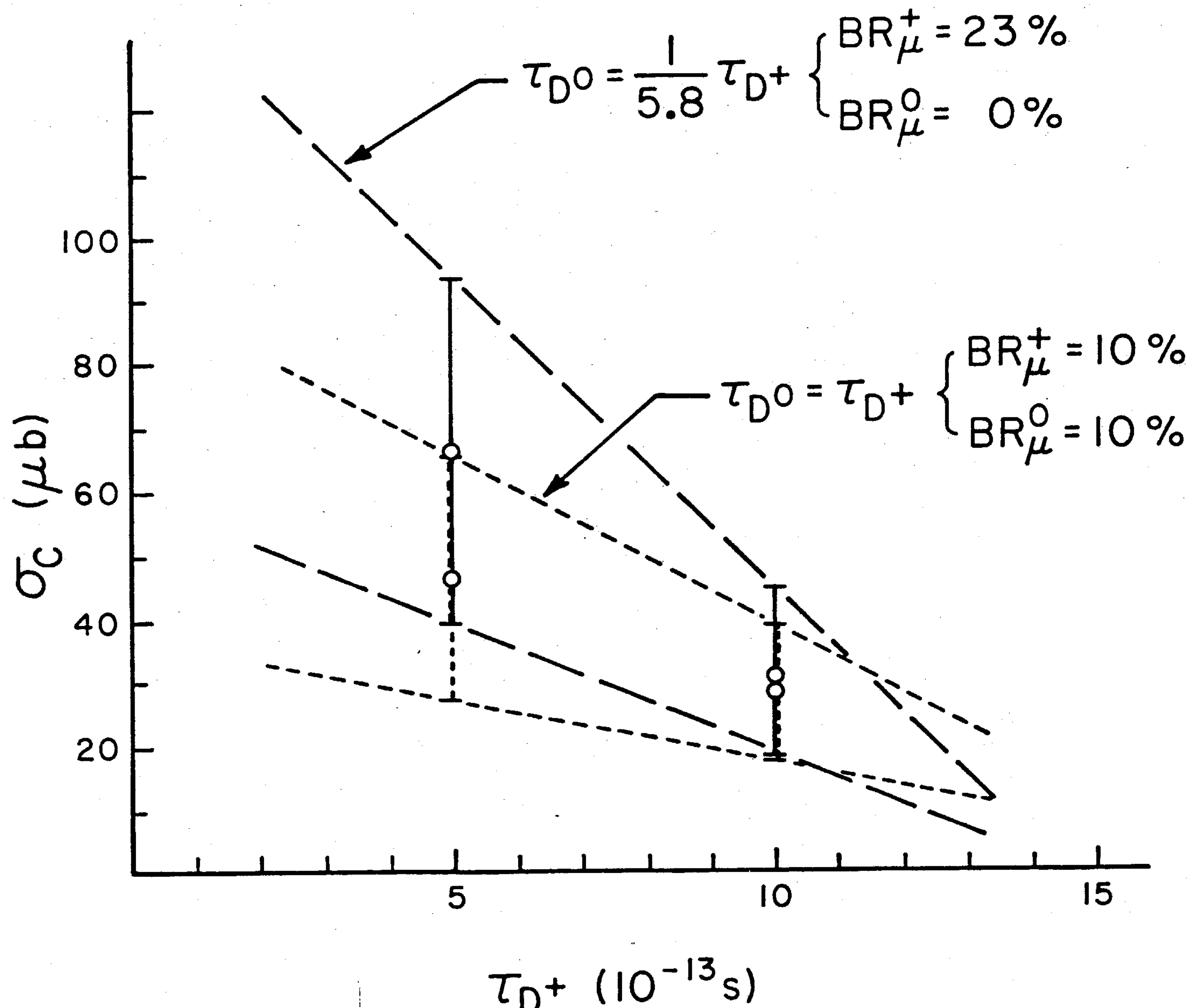
1. The experimental arrangement, including the streamer chamber, beam defining counters, interaction hodoscope and muon filter.

2. Definitions of event categories and data from the muon trigger sample displayed on a plot of length vs. laboratory angle. The squares represent all events having projected production angle $\gtrsim 13^{o}$. Open circles represent events for which the track not associated with the primary vertex is possibly but not uniquely a muon. The two triangles represent events for which this "decay track" is a uniquely identified muon.

3. The relationship between the charm production cross section and the lifetime of the $D^{\pm}$ implied by this experiment, for the two assumptions discussed in the text.

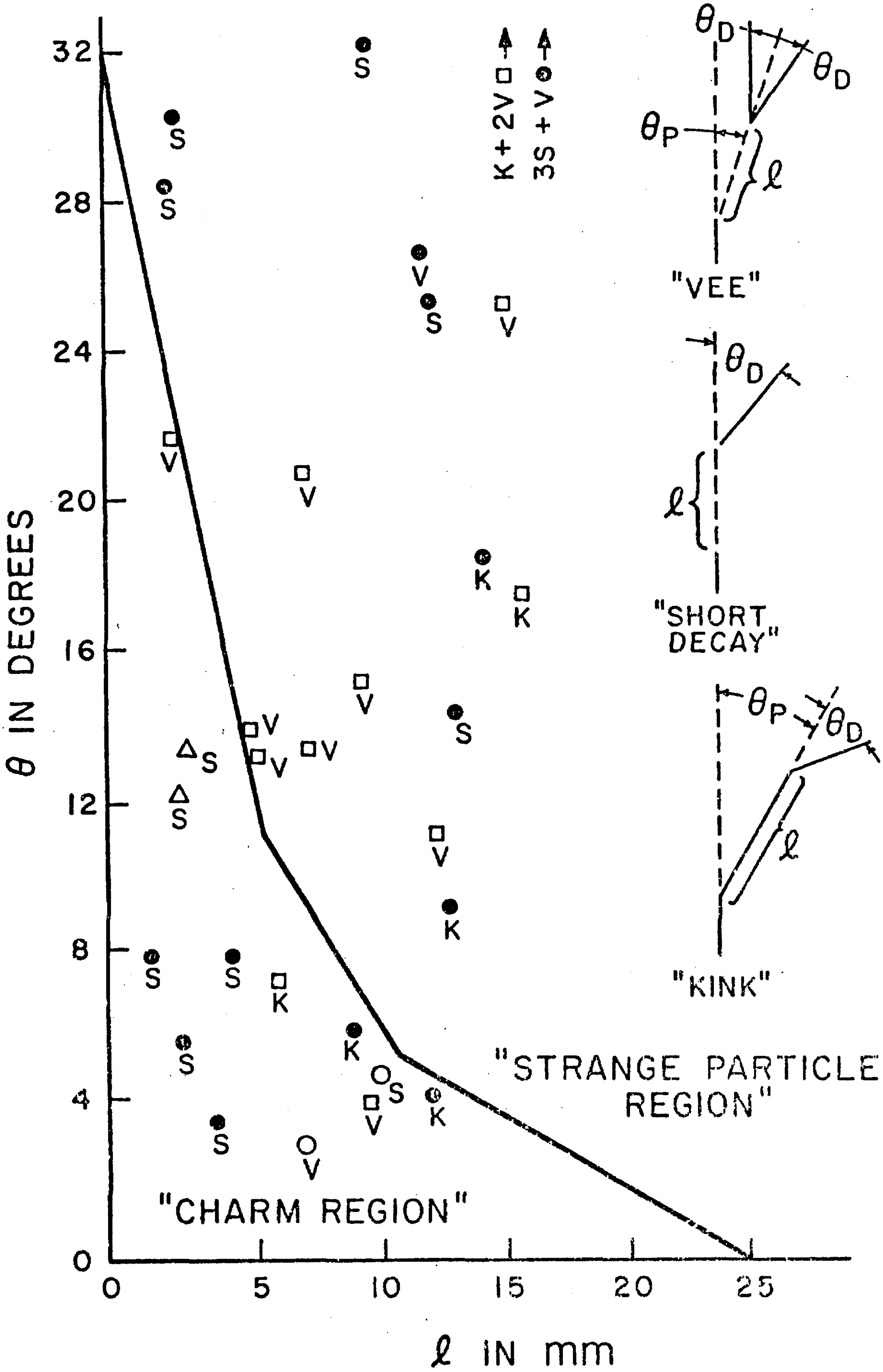


BEAM
VH1
VH2
B1
B2
INTERACTION
HODOSCOPE
STEEL HADRON FILTER
A
MWPC
B
MWPC
INNER CONE VETO
MWPC
μ HODOSCOPE
μ' HODOSCOPI
CONCRETE
SHIELDING
BLOCKS



$\tau_{D^0} = \frac{1}{5.8}\tau_{D^+}$ $\begin{cases} BR_\mu^+ = 23\% \\ BR_\mu^0 = 0\% \end{cases}$
$\tau_{D^0} = \tau_{D^+}$ $\begin{cases} BR_\mu^+ = 10\% \\ BR_\mu^0 = 10\% \end{cases}$
σ_c (μb)
100
80
60
40
20
5
10
15
τ_{D^+} (10^{-13}s)

Fig. 3



32
28
24
20
16
12
8
4
0
θ IN DEGREES
0
5
10
15
20
25
ℓ IN mm
K + 2V
3S + V
θD
θD
θP
ℓ
"VEE"
θD
ℓ
"SHORT DECAY"
θP
θD
ℓ
"KINK"
"STRANGE PARTICLE REGION"
"CHARM REGION"